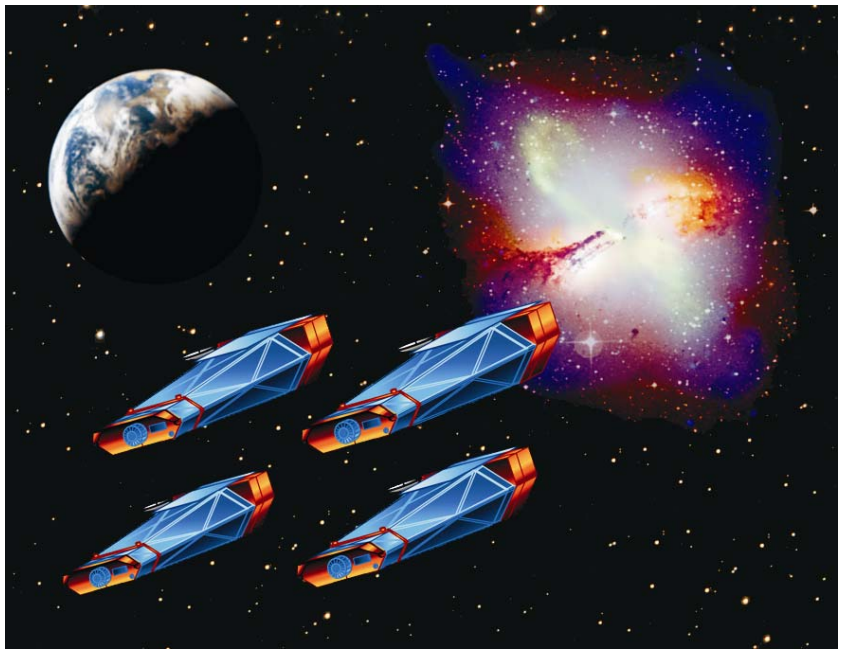
Probing Dark Energy with Constellation-X

Steve Allen, KIPAC (Stanford/SLAC)



In collaboration with:

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Alexey Vikhlinin (CfA)

and the Con-X FST

Dark Energy Task Force
Call for White Papers

In February 2005 the NSF-NASA-DOE Astronomy and Astrophysics Advisory Committee (AAAC) and the NSF-DOE High Energy Physics Advisory Panel (HEPAP) established a Dark Energy Task Force (DETF) as a joint subcommittee to advise NSF, NASA, and DOE on the future of dark energy research.

The DETF was asked to advise the agencies on the optimum near- and intermediate-term programs to investigate dark energy and, in cooperation with agency efforts, to advance the justification, specification and optimization of a ground-based Large Survey Telescope (LST) and a space-based Joint Dark Energy Mission (JDEM). The DETF will prepare a final report for submission to the AAAC and HEPAP with a target date of December 2005.

In particular, the DETF was charged to:

1. Summarize the existing program of funded projects by projected capabilities, systematics, risks, required documents, and progress-to-date.
2. Summarize proposed and emergent approaches and techniques for dark energy studies; that is, characterize these approaches and techniques by the added value the projected capabilities would provide to the investigation of dark energy.
3. Identify important steps, precursors, R&D and other projects that are required in preparation for JDEM, LST and other existing or planned experiments.
4. Identify any areas of dark energy parameter space that the existing or proposed projects fail to address.

We expect that the DETF will prioritize techniques for studying dark energy but will not rank specific projects.

Our response (June 2005)

White paper: "Probing Dark Energy with Constellation-X"

ABSTRACT: (edited)

Con-X will carry out two powerful and independent sets of tests of dark energy based on X-ray observations of clusters.

The first group of tests will measure the absolute distances to clusters, primarily using measurements of the X-ray gas mass fraction in the largest dynamically relaxed clusters, but with additional power provided by follow-up observations of the Sunyaev-Zel'dovich (SZ) effect. Like SNIa studies such data $\rightarrow$ d(z). As with SNIa, we are `cherry picking' the best/easiest objects to work with.

The second, independent group of tests will use the high res. spatial/spectral capabilities of Con-X to determine precise scaling relations between X-ray/SZ observables and mass. Together with future X-ray/SZ surveys, these data will constrain the growth of structure, which is also a sensitive function of dark energy.

Con-X data will constrain dark energy with comparable accuracy and in a beautifully complementary manner to the best other techniques available ~2018.

Methods and current results

Method 1: X-ray gas mass fraction

BASIC IDEA: Galaxy clusters are so large that their matter content should provide a fair sample of matter content of Universe.

Chandra (+ lensing) data → robust total mass measurements
Chandra data → (very) precise X-ray gas mass measurements

If we define:

$$f_{gas} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}} \qquad f_{gal} = 0.19h^{0.5} f_{gas}$$

Then:

$$f_{baryon} = f_{gal} + f_{gas} = f_{gas}(1 + 0.19h^{0.5})$$

Since clusters provide ~ fair sample of Universe $f_{baryon} = b\Omega_b/\Omega_m$

$$\Omega_m = \frac{b\Omega_b}{f_{baryon}} = \frac{b\Omega_b}{f_{gas}(1+0.19h^{0.5})}$$

The bias factor

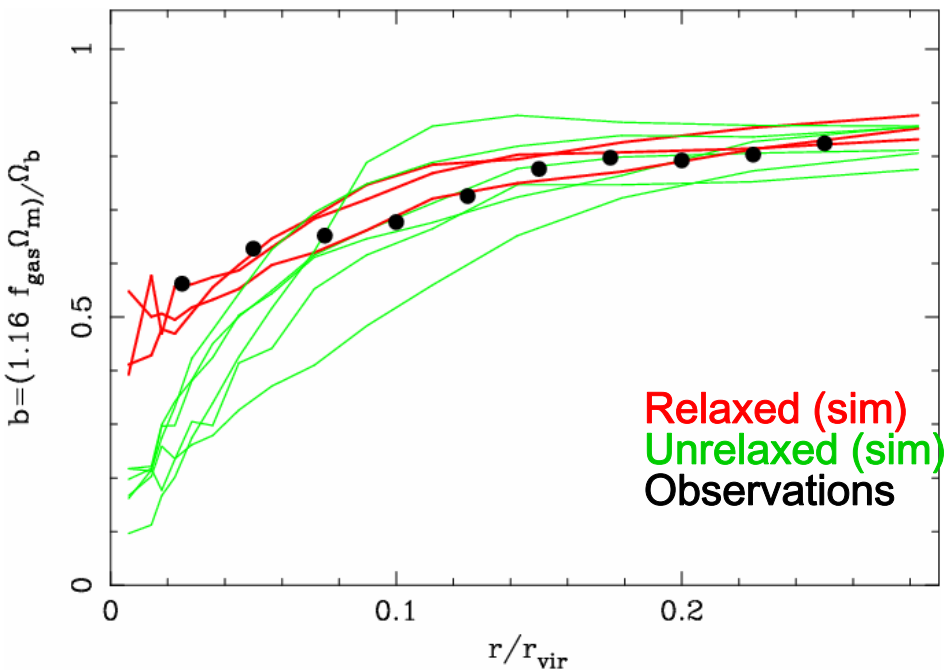
Simulations:

$$f_{baryon} = b\frac{\Omega_b}{\Omega_m}$$

For $r=0.25r_{vir}$ (Chandra obs.)

b = 0.83±0.03

Eke et al 98



Simulations indicate that baryonic mass fraction in clusters is slightly lower than mean value for Universe as a whole. (Some gas is lifted beyond the virial radius by shocks e.g. Evrard '90, Thomas & Couchman '92, NFW '95 etc).

To account for possible residual uncertainties in b and Chandra calibration we also introduce additional 10% systematic uncertainty → b=0.83±0.09

The current Chandra data:

Chandra observations of 41 X-ray luminous, dynamically relaxed clusters:

$0.06<z<1.07$ $L_X>10^{45}h_{70}^{-2}$ erg/s kT>5keV

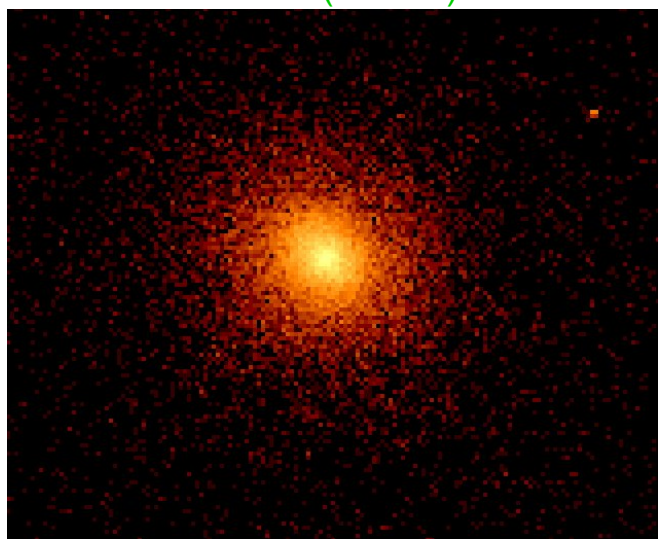
All have regular X-ray morphology, sharp central X-ray surface brightness peak, minimal X-ray isophote centroid variation.

MACS + BCS SURVEYS
(Ebeling et al. '98, '01, '05):

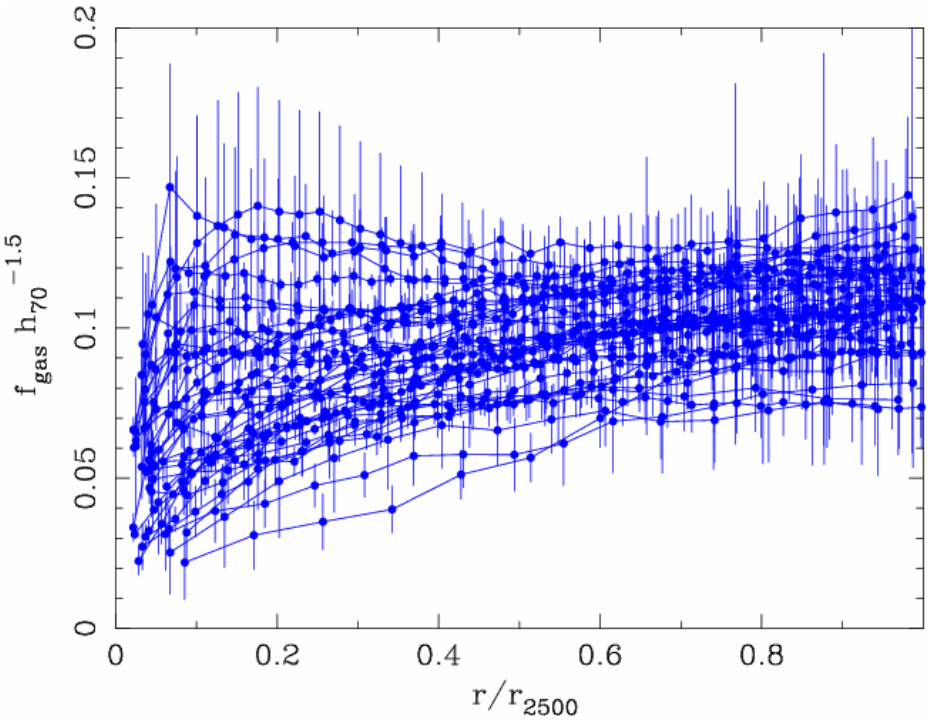
120 clusters at $z>0.3$ with $L_X>10^{45}$erg/s (>30x improvement over previous samples). Chandra snapshot programs lead by Leon van Speybroeck and Harald Ebeling.

This data release 41 clusters (1.6 Ms). Previous data release 26 clusters (0.8Ms). Archival data + DDT program

MACS1423+24 (z=0.54) 120ks



Chandra results on $f_{gas}(r)$



41 regular, relaxed clusters:

$f_{gas}(r)$ large scatter at small radius but → approximately universal value at r_{2500}

Fit constant value at r_{2500}

$f_{gas}(r_{2500})=(0.110\pm0.002)h_{70}^{-1.5}$
$f_{gas}(r_{2500})=(0.0688\pm0.0088)h^{-1.5}$

For $\Omega_b h^2=0.0214\pm0.0020$ (Kirkman et al. '03), $h=0.72\pm0.08$ (Freedman et al. '01), $b=0.83\pm0.09$ (Eke et al. 98 +10% systematics)

$$\Omega_m = \frac{(0.83\pm0.09)(0.0437\pm0.0041)h_{70}^{-0.5}}{(0.1110\pm0.002)(1+0.16h_{70}^{0.5})} = 0.27\pm0.04$$

Dark Energy constraints: measuring $f_{gas}(z)$

We expect true $f_{gas}(z)$ values to be approximately constant with redshift. However, measured $f_{gas}(z)$ values depend upon assumed distances to clusters $f_{gas} \propto d^{1.5}$. This introduces apparent systematic variations in $f_{gas}(z)$ depending on the differences between the reference cosmology and the true cosmology.

SCDM (Ω_m=1.0, Ω_Λ=0.0)

ΛCDM (Ω_m=0.3, Ω_Λ=0.7)

Inspection clearly favours ΛCDM over SCDM cosmology.

To quantify: fit ΛCDM data with model which accounts for apparent variation in $f_{gas}(z)$ as underlying cosmology is varied (Ω_m,Ω_Λ) → find model that provides best fit to data.

$$f_{gas}(z) = \frac{b(z)\Omega_b}{(1+0.19\sqrt{h})\Omega_m}\left[\frac{d_A{}^{LCDM}(z)}{d_A{}^{model}(z)}\right]^{1.5}$$

ΛCDM Cosmology:

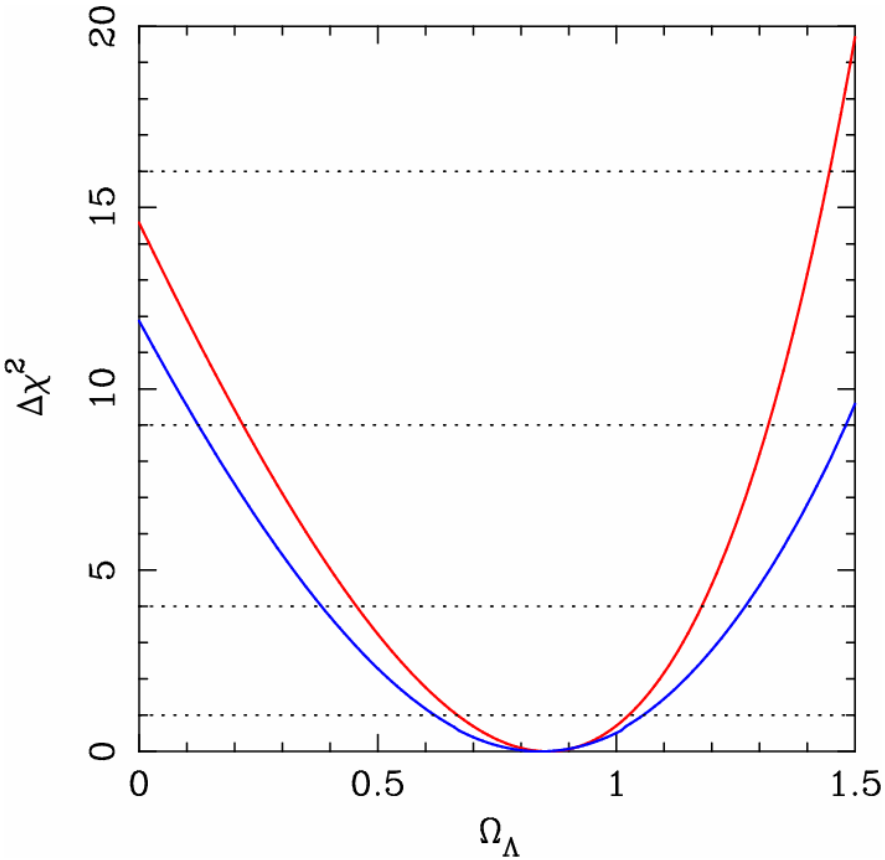
Using standard priors:
($\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08, b=0.83±0.09)

Best-fit parameters (ΛCDM):

Ω_m=0.27±0.04, Ω_Λ=0.86±0.19

(Note also good fit: χ^2=47/39)

Marginalized results on dark energy (ΛCDM)



Red: standard priors (Ω_Λ=0.86±0.19)

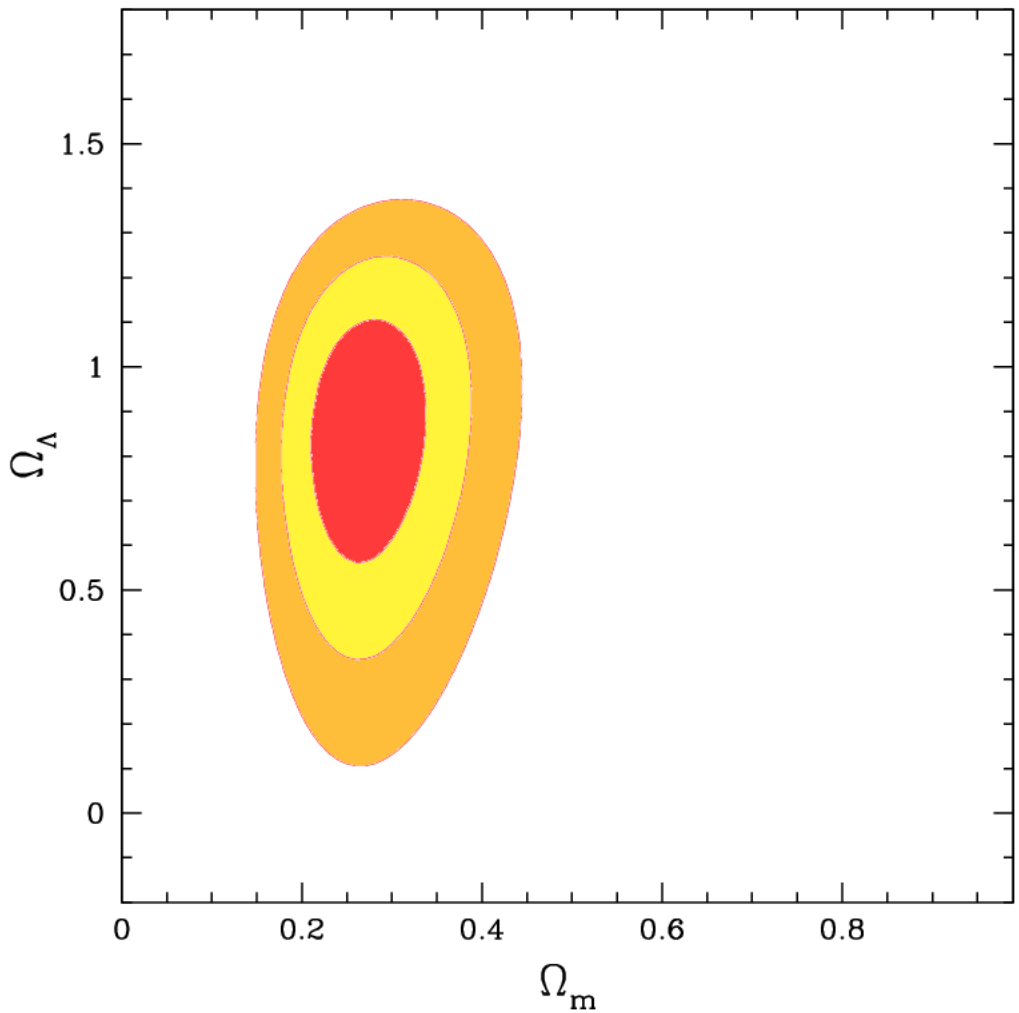
Blue curve: weak priors ($\Omega_b h^2$=0.0214±0.0060, h=0.72±0.24, b=0.83 ±0.27)

Ω_Λ = 0.86±0.22

Detection of effects of DE at >3σ (>99.99% MC) using weak priors.

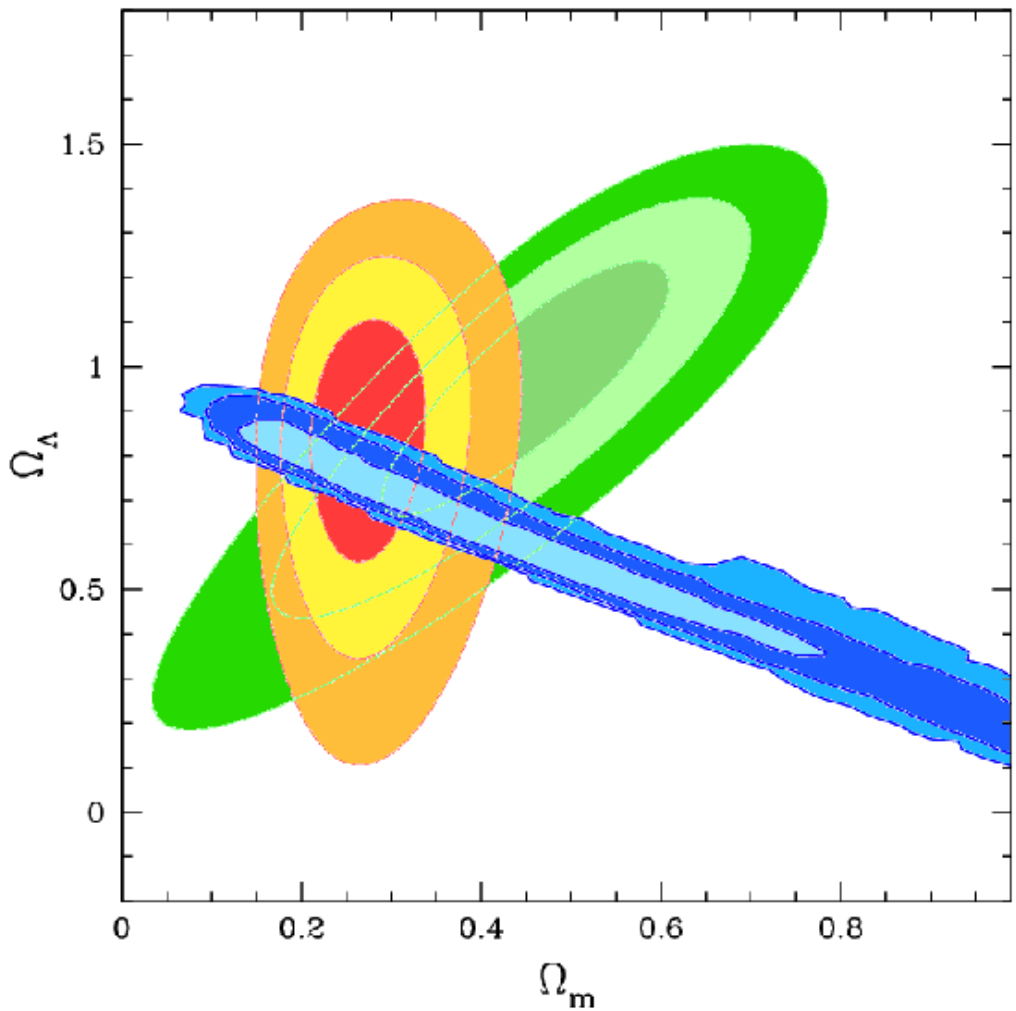
The Chandra f_{gas}(z) data like SNIa data show that the Universe is accelerating.
Like SNIa, the f_{gas}(z) data measure d(z) and with comparable accuracy!
But the physics is independent and simple!

Comparison of independent constraints (ΛCDM)



Cluster f_{gas} analysis including standard $\Omega_b h^2$, h and b priors.

Comparison of independent constraints (ΛCDM)



Cluster f_{gas} analysis including standard $\Omega_b h^2$, h and b priors.

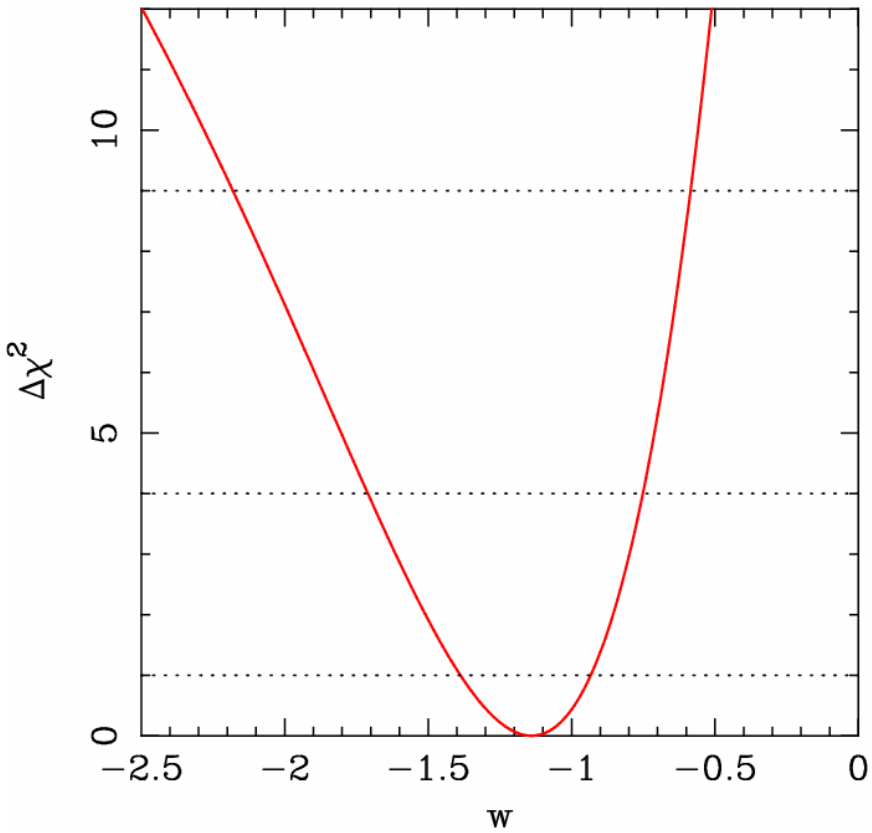
CMB data (WMAP +CBI + ACBAR) weak prior $0.3<h<1.0$

`Gold' Supernovae data from Riess et al. (2004).

Constraining w

The dark energy equation of state parameter, w

If we assume flatness, we can also use the $f_{gas}(z)$ data + standard priors on $\Omega_b h^2$, h and b priors to constrain $w=p/\rho$.



For constant w models we measure:

w=-1.14 (+0.21,-0.25)

(consistent with ΛCDM).

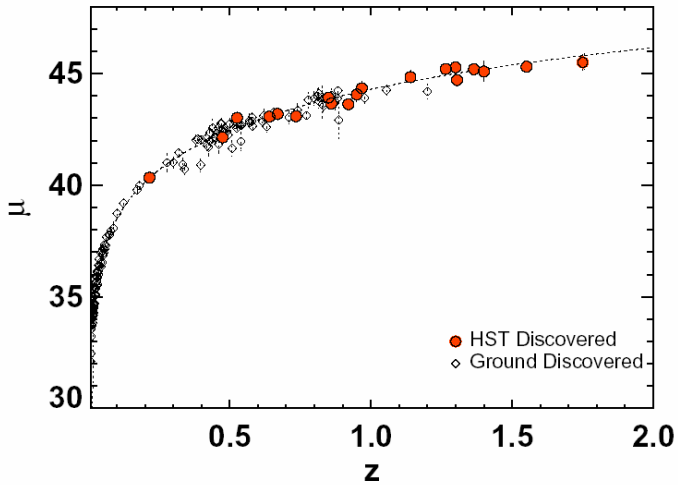
But real power of these data for dark energy work is only seen when used in combination with other complementary data (especially CMB).

Measuring w: combined analysis approach

USE: Best available data → tight constraints, minimize systematics.
Complementary data → minimize priors.
General DE models → robust constraints.

DATA USED:

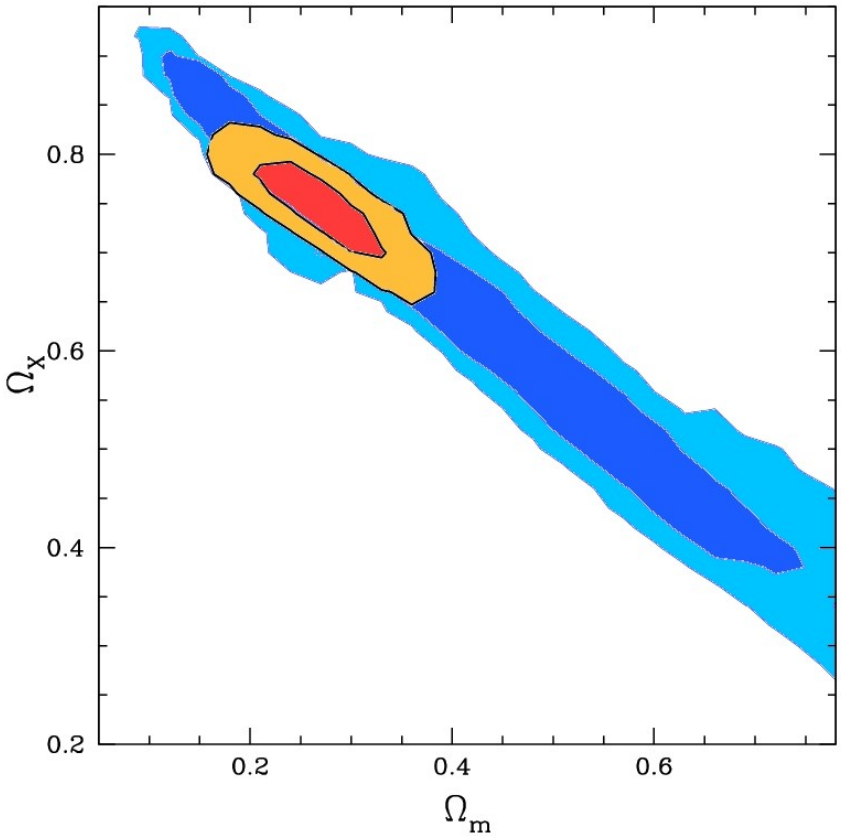
1) Chandra $f_{gas}(z)$ (26 clus: Allen et al 2004)
2) CMB: WMAP (TT/TE)+CBI+ACBAR
3) SNIa (Riess et al. 2004 GOLD SAMPLE)



Analyse using enhanced version of CosmoMC code (Lewis & Bridle 2002). Markov Chain Monte Carlo (MCMC) method. Note analysis of CMB data includes treatment of DE perturbations for models crossing w=-1 (Rapetti & Weller 04).

Complementarity: CMB+f_{gas}(z) (non-flat, no hidden priors)

The combination of CMB+f_{gas}(z) data breaks key parameter degeneracies



A) DE vs. matter density:

68.3 and 95.4% confidence:

Blue: CMB only.
Red: f_{gas}(z)+CMB data

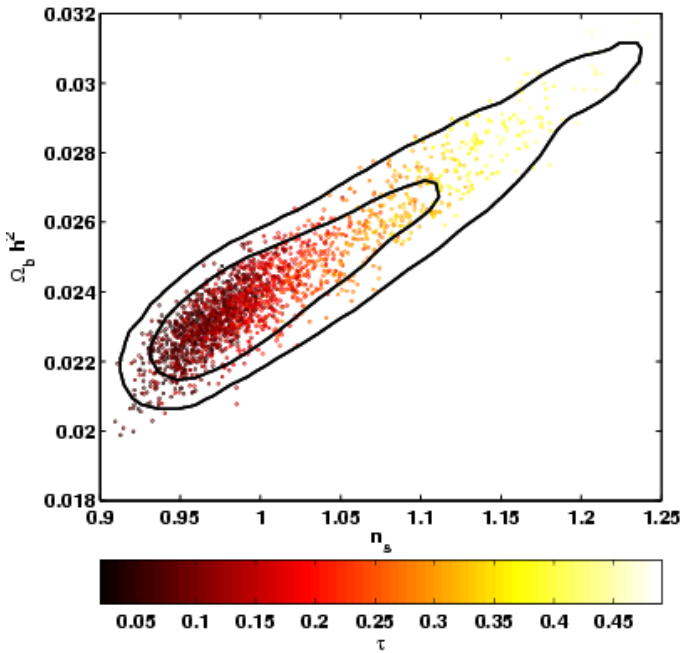
Marginalized results:

$\Omega_{DE} = 0.75 \pm 0.04$
$\Omega_m = 0.26 \pm 0.05$

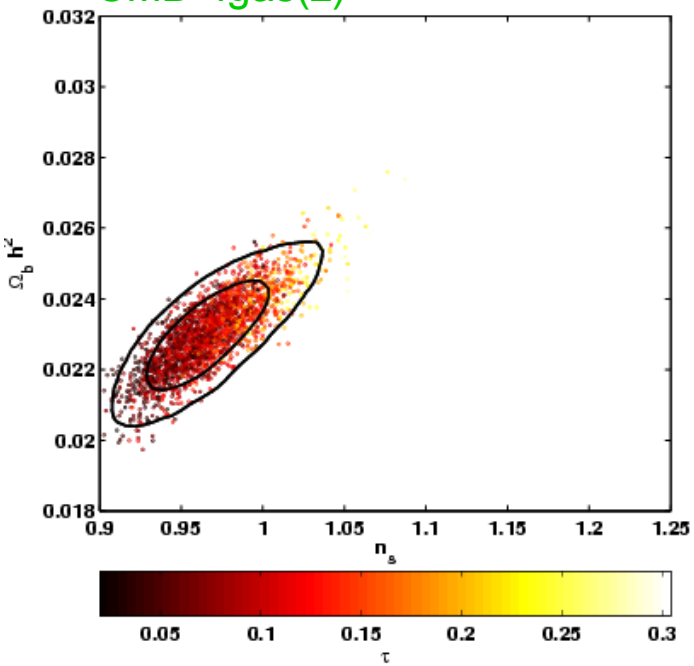
Complementarity: CMB+f_{gas}(z) (flat, no hidden priors)

The combination of CMB+f_{gas}(z) data breaks key parameter degeneracies

CMB+SNIa

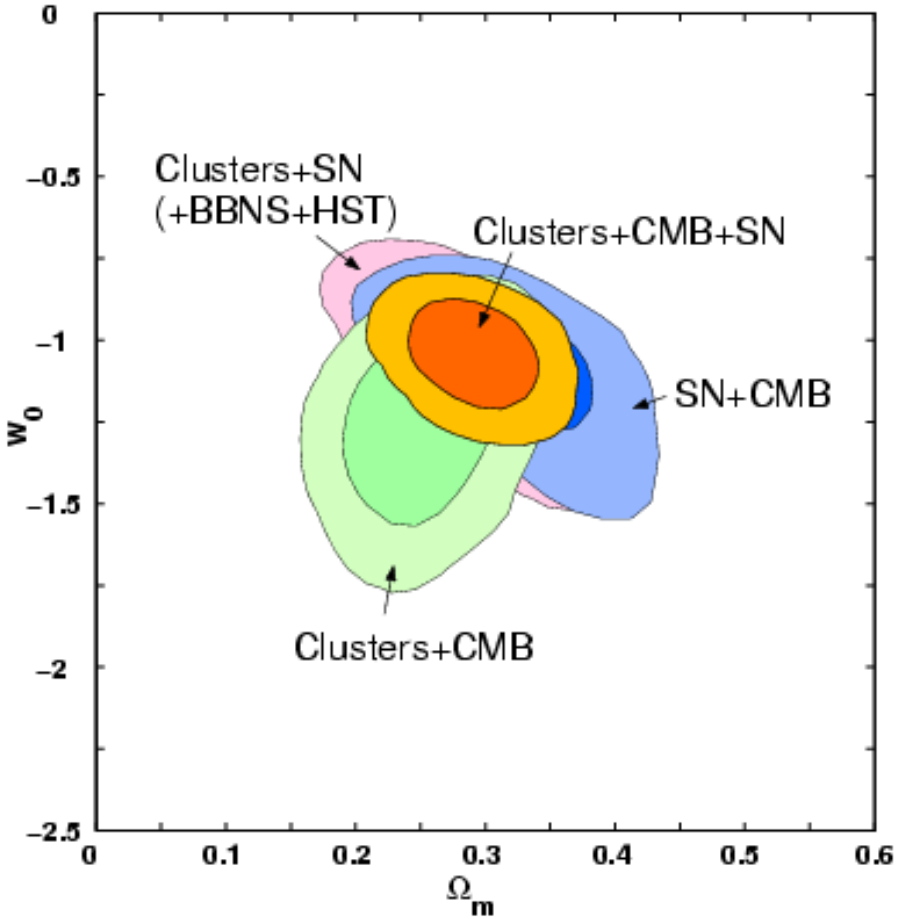


CMB+fgas(z)



The breaking of parameter degeneracies means that no further, external priors are required in the analysis unlike most previous work (e.g. τ<0.3 by WMAP team).

Constraints for data pairs and 3 data sets combined



Constant w model:

Analysis assumes flat prior.

68.3, 95.4% confidence limits for all three parameter pairs consistent with each other.

Marginalized constraints (68%)

$\Omega_m = 0.29 \pm 0.03$
$w_0 = -1.05 \pm 0.11$
$\chi^2_\nu = 1.03$

(Rapetti, Allen & Weller 2005)

A few notes on systematics

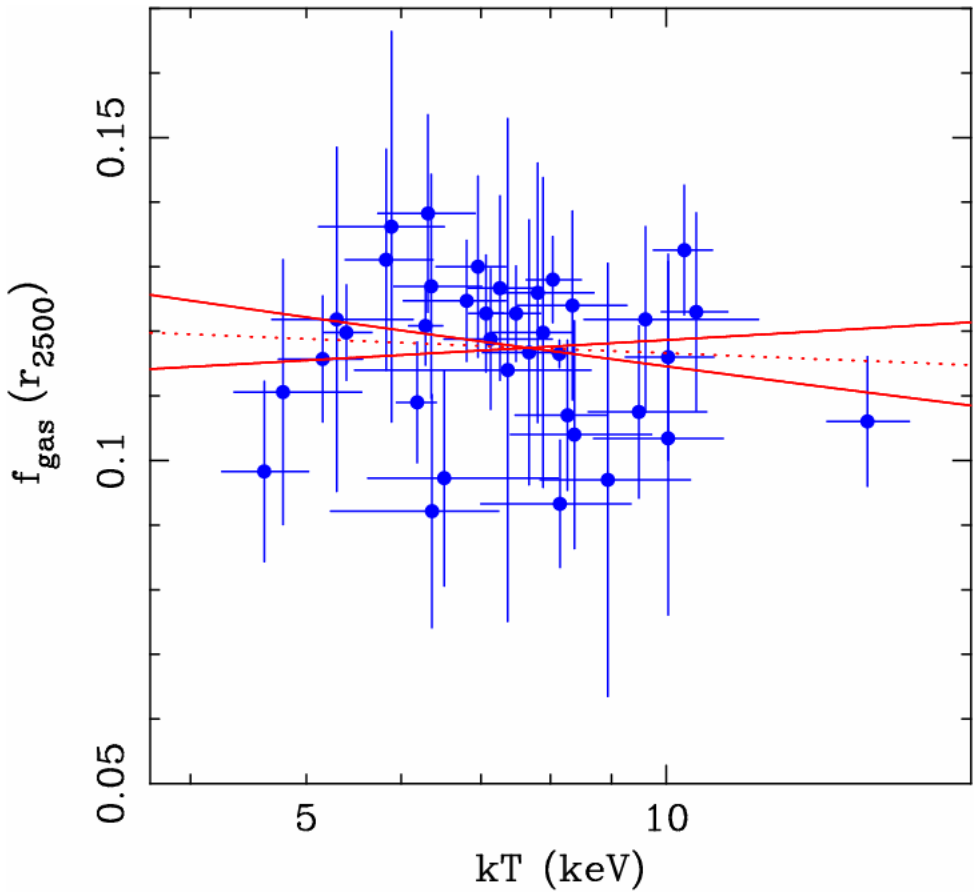
Scatter in the fgas data

The scatter in the current Chandra fgas data for 41 clusters is LOW.

The weighted mean scatter about the best-fitting model is only 12%, which translates to only 8% in distance (comparable to SNIa).

No sign as yet of systematic scatter with acceptable χ^2. Method offers the prospect to probe cosmic acceleration with high precision (Con-X/XEUS)

A systematic trend with temperature?



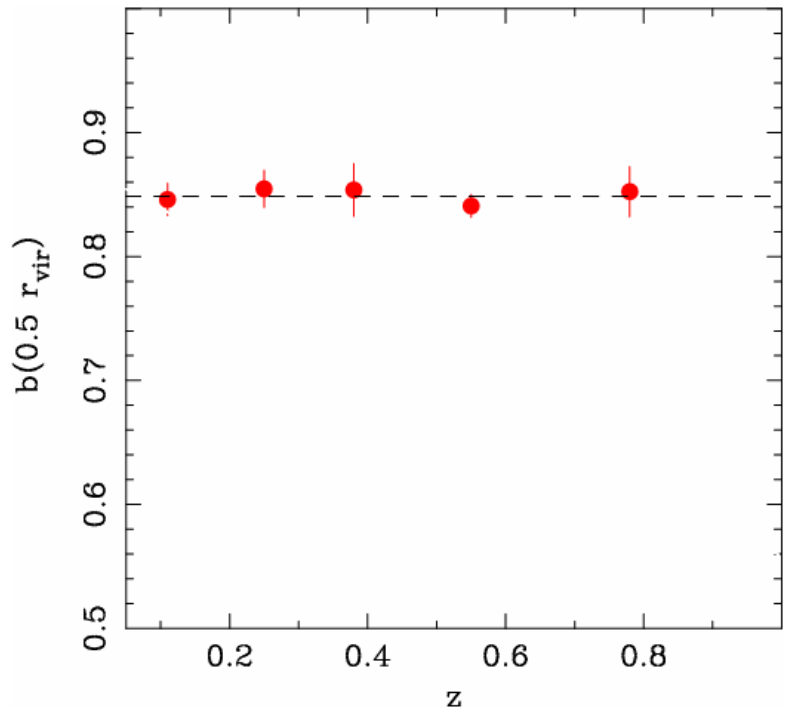
NO. THINGS LOOK GOOD!

Best fitting power-law model is consistent with a constant model at 1 sigma.

We find no evidence for a trend of fgas with kT in the current Chandra data.

Evolution of the bias factor with redshift:

We have assumed that largest galaxy clusters to provide similarly fair samples of matter content of Universe at all redshifts i.e. b(z)=const. Is this valid?



Simulations: Eke et al '98

Available simulations for large (kT>5keV) relaxed clusters suggest little/no evolution of bias factor within $0.5r_{vir}$ for z<1.

The simulations need to be improved. For Con-X we will need to know b(z) to 1% accuracy and pin down optical component. We and others are starting to work on this.

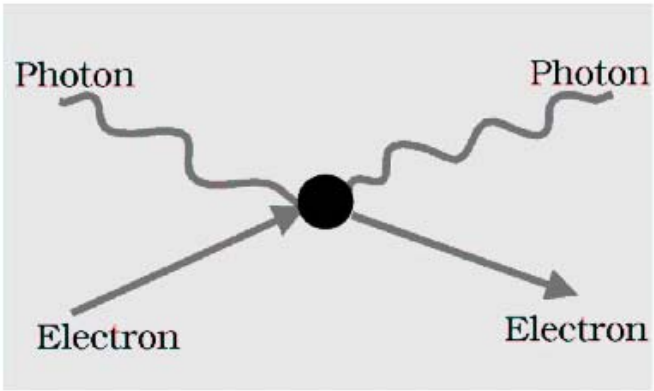
Assuming a flat ΛCDM model, what are the best-fit Ω_m and db/dz?

$$\Omega_m = 0.27 \pm 0.04, \quad db/dz = -0.035 \pm 0.060$$

X-ray + SZ studies with Con-X

Method 2: Combined X-ray + SZ studies

We can also measure distance independently of redshift by combining X-ray+SZ observations of galaxy clusters.



$$y(b) \propto \int n_e T dl$$

$$d(z) = d^{ref}(z)\left[\frac{y_{obs}}{y_{ref}}\right]^2$$

Predicted by Con-X data for given reference cosmology

This work is still in its infancy (though some results) with errors dominated by systematic/statistical uncertainties in SZ measurements (though improving).

An excellent, direct complement to fgas work, increasing power of the distance measurements (can analyse separately or `bolt-on' SZ data where available).

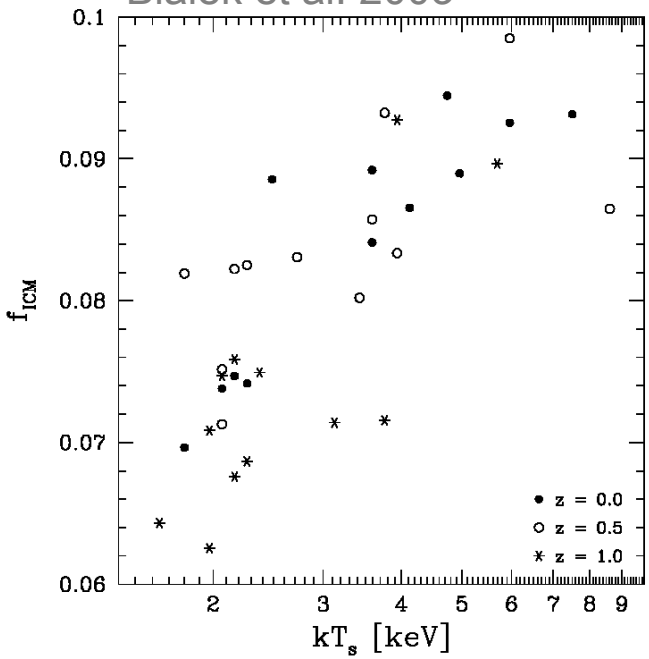
Considerations for Con-X observations and Instrumentation

These are still pretty rough ideas. Detailed simulations are needed.

Which clusters should we target with Con-X?

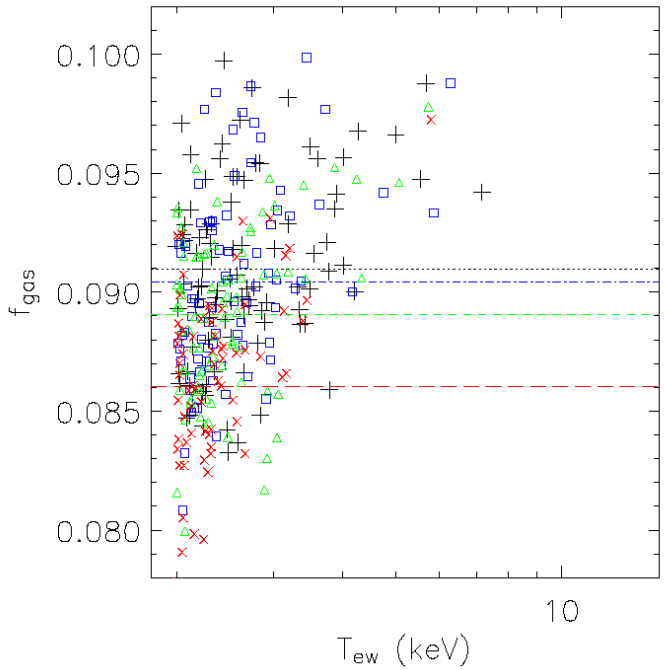
1) <u>THE BIGGEST, HOTTEST CLUSTERS (kT≥5keV):</u> (which are also the brightest at a given redshift). Crucially, the bias factor, b, exhibits reduced scatter and is ~ constant for kT>5 keV (maybe push to 4 keV). In the end (large samples) this scatter will limit the accuracy of the DE constraints.

Bialek et al. 2003



[Δ=200]

Ettori et al 2004

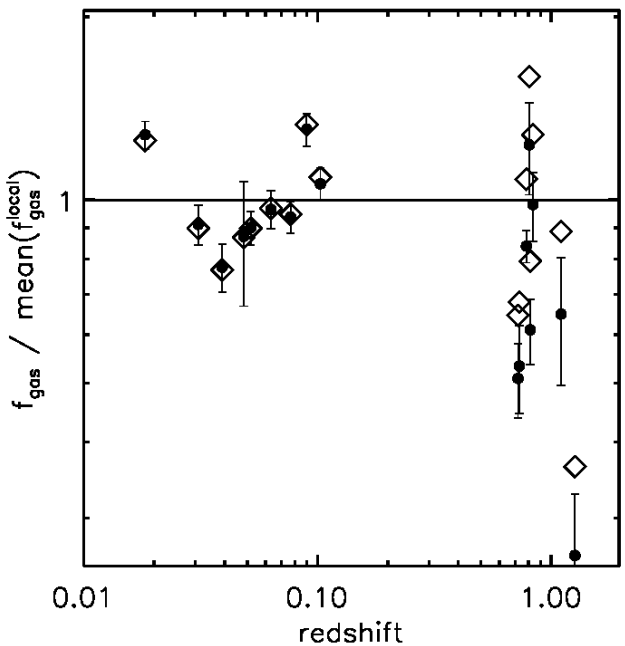


[Δ=500]

Which clusters should we target with Con-X?

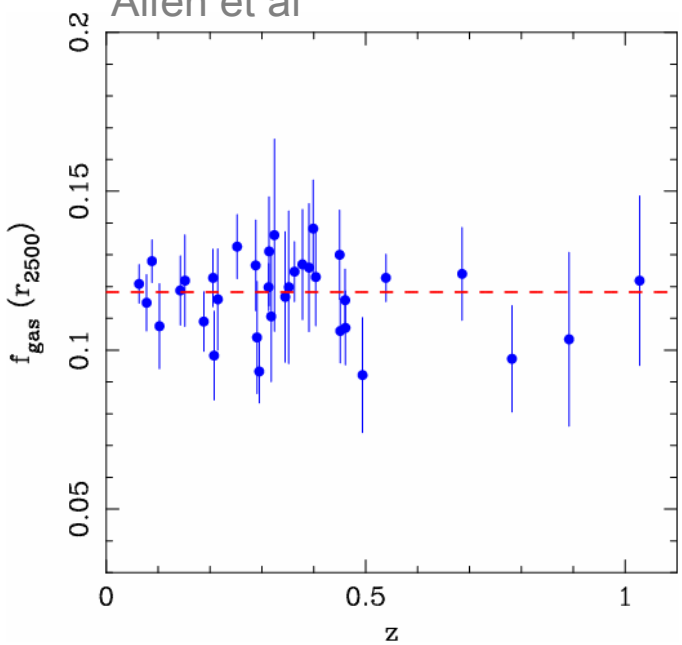
2) RELAXED CLUSTERS: The primary source of systematic scatter in previous studies of the baryonic mass fraction in clusters had been the inclusion of clusters with a wide range of dynamical states. [For reference, ~25% of clusters in MACS (same LX, 0.3<z<0.7) are relaxed enough.]

Ettori et al. 2003



All clusters → bad χ^2

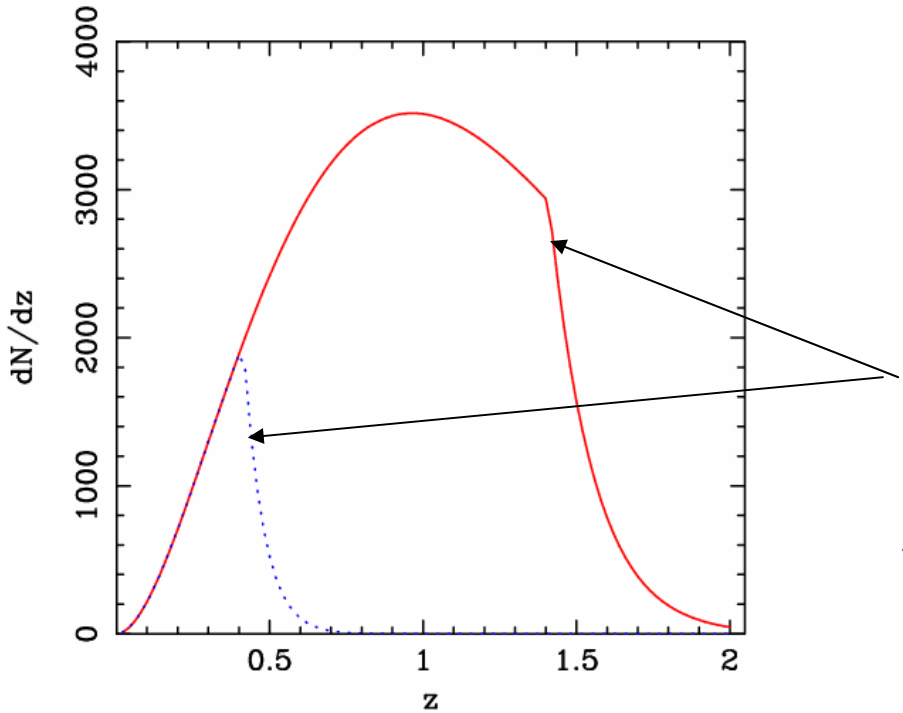
Allen et al



Relaxed clusters (25%) → good χ^2

How many clusters could we target with Con-X?

In principle, enough relaxed massive clusters should exist to allow us to construct samples of 250-500 clusters with fgas/predicted SZ fluxes at 3.5%-5% precision.



Number of clusters with $L_X > 2\times10^{45} h_{70}^{-2}$ erg/s for standard LCDM cosmology.

$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.8$

Flux limits 1.2×10^{-12} erg/cm^2/s (MACS) and 5×10^{-14} erg/cm^2/s in the 0.1-2.4 keV band.

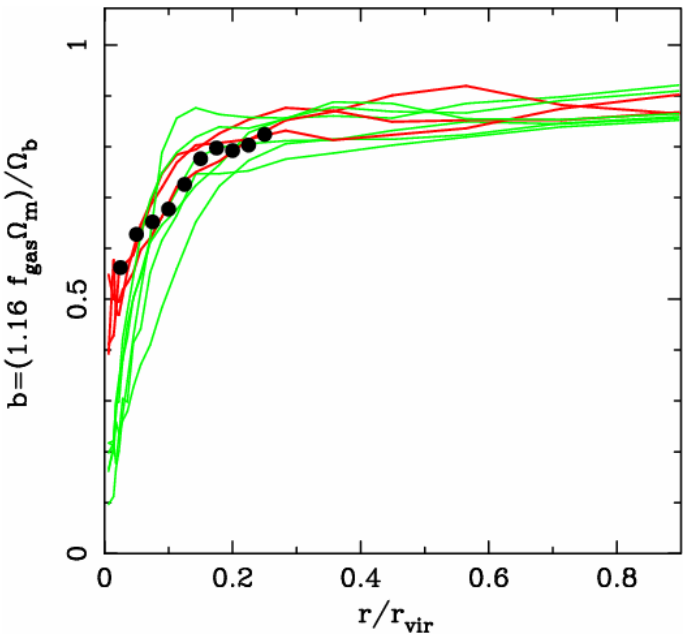
Assume 1/4 -1/8 clusters relaxed and standard evolution of H(z).

We will require a precursor, large area X-ray (ideal) or SZ survey.

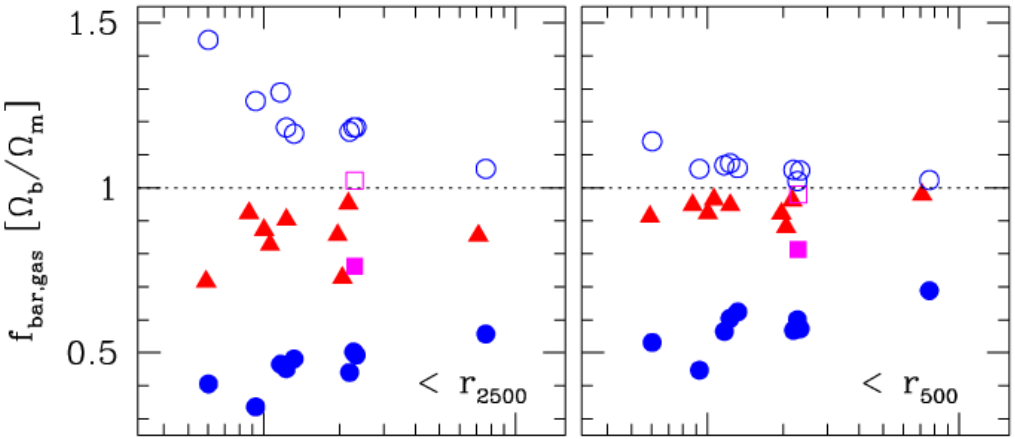
FOV and background considerations

What radius to we want to measure fgas (predict SZ flux) at?: With Chandra we measure at r_{2500} (~$0.25r_{vir}$) but with Con-X the **minimum** radius to go for should be r_{500}(~$0.6r_{vir}$) since the scatter in b reduces substantially → better constraints on DE.

Eke et al. 2003



Kravtsov et al 2005



FOV and background considerations

In order to measure fgas easily at radii $\geq r_{500}(\sim 0.6 r_{vir})$ for z>0.3, we require a field of view of at least 8-10 arcmin in size.

Note: r_{500}~4-5 arcmin for a big cluster at z=0.3
r_{500}~2-3 arcmin for a big cluster at z=0.5
r_{500}~1-2 arcmin for a big cluster at z=1.0

The large FOV will facilitate on chip background subtraction at high-z and allow us to study nearby clusters effectively. Note that it NOT necessary to have high spectral resolution across this whole field (CCD resolution is sufficient for the bulk of the dark energy/cosmology work).

(High spectral resolution for part of the central FOV is v. important though.)

PARTICLE BACKGROUND The net particle background must be lower (by factor of a few) than for Chandra/XMM if we are to make measurements at radii $\geq r_{500}$ comfortably.

What resolution (spatial/spectral) needed?

SPECTRAL RESOLUTION There is great advantage to having high spectral resolution available over at least a small central area (few arcmin across) for studying detailed cluster physics and testing key assumptions (eg temperature structure, hydrostatic equilibrium) for a subsample of objects.

This is needed for Con-X to make a major contribution to growth of structure studies (providing precise, accurate mass measurements.)

Question: high-res calorimeter inside a lower-res larger array?

SPATIAL RESOLUTION We need to identify relaxed clusters, separate dynamically active regions of clusters + remove contaminating point sources.

Spatial resolution of $\leq$ 5 arcsec FWHM is ideal for this work.

Detailed simulations are required to see how well we can do with poorer spatial resolution. My expectation is that 15" resolution is probably not sufficient to do all we'd wish to for high-z extended sources. (Note 10" = 50kpc at z~1; r_{500}~1-2 arcmin for a big cluster.) Please give us all the spatial resolution you can!

Collecting area:

The baseline collecting area is fine for this work.

Con-X Strategy and predicted results

Baseline proposal: fgas(z) and X-ray+SZ studies

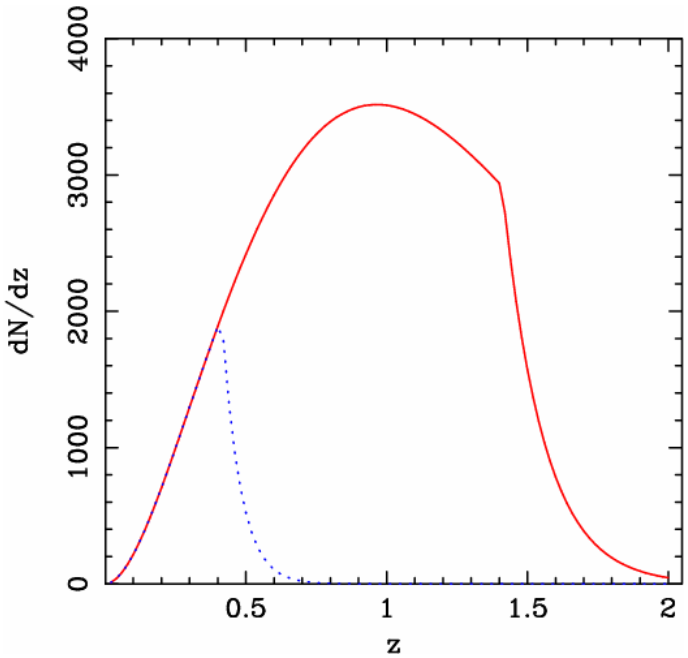
Use 10-15% of available time over first 5 years of Con-X mission (10-15Ms).

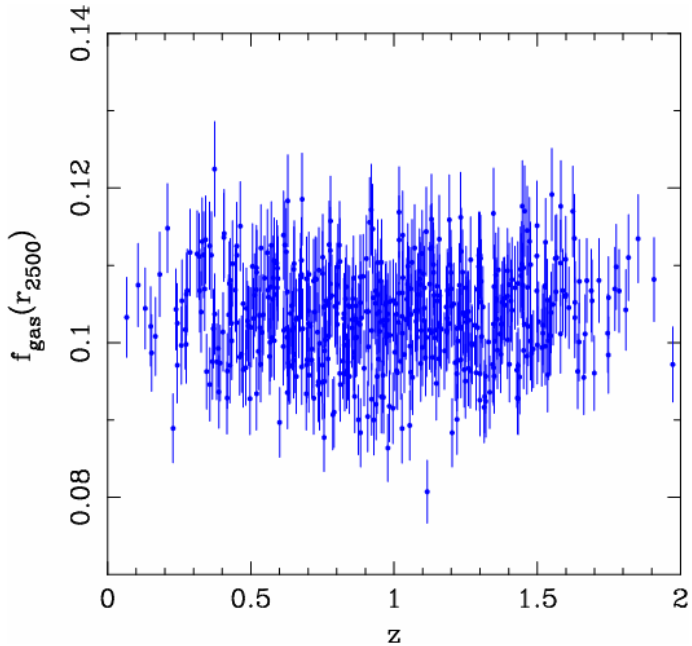
STEP 1: First take ~1ks snapshots of ~2000 most massive clusters detected from precursor X-ray and/or SZ surveys → identify largest relaxed systems. (2 Ms total time)

STEP 2: The resulting sample of 250-500 clusters will then be targeted for 20-40ks each, allowing us to measure fgas and/or predict the Compton y-parameter to 5% or 3.5% accuracy, respectively. (10 Ms total time)

The following results should be achievable….

Predicted Con-X fgas data set

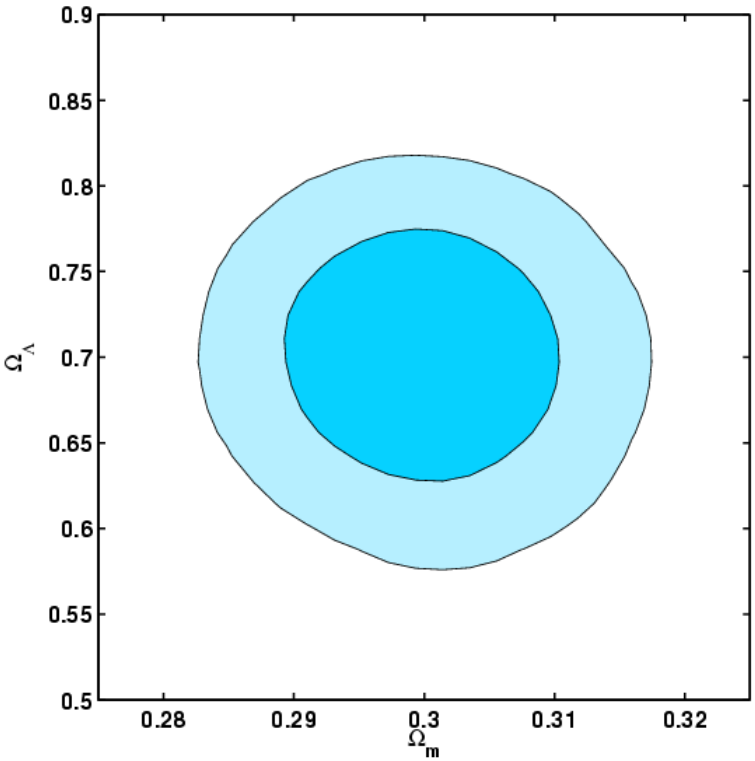


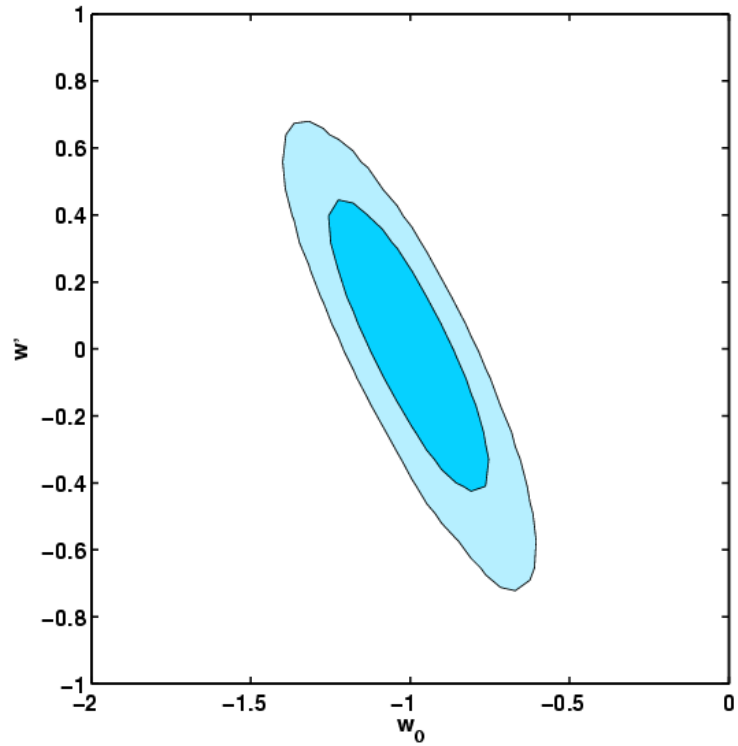


Con-X (in combination with future cluster surveys) will expand the size of fgas(z) samples by an order of magnitude. The data at high-z will have the same quality as the best current data obtained at low-z from Chandra and XMM-Newton. Median redshift z~1 with sample stretching to z~2.

Example: all-sky $L_{Bol}>2\times10^{45}$erg/s, $Fx>5\times10^{-14}$erg/cm^2/s (0.1-2.4keV).

Constraints from Con-X data alone

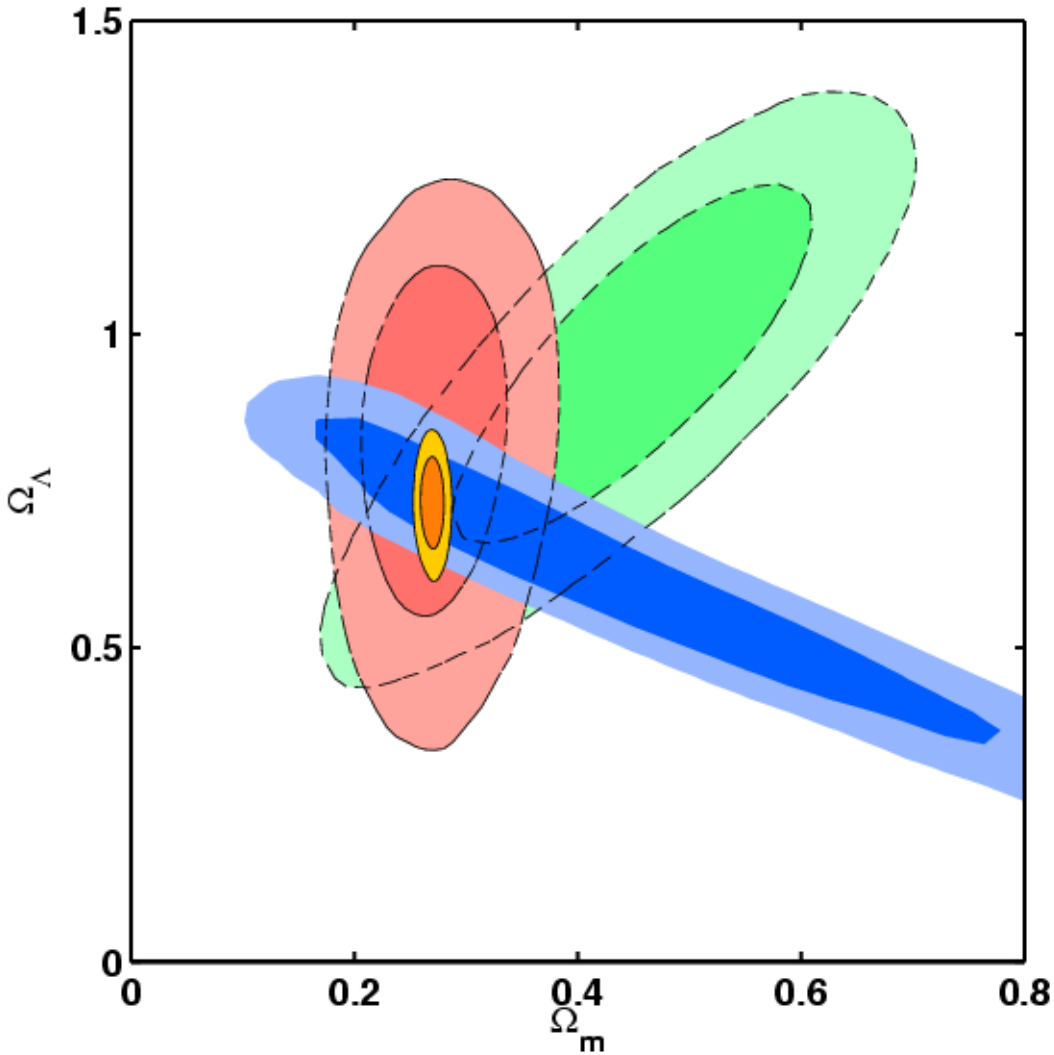




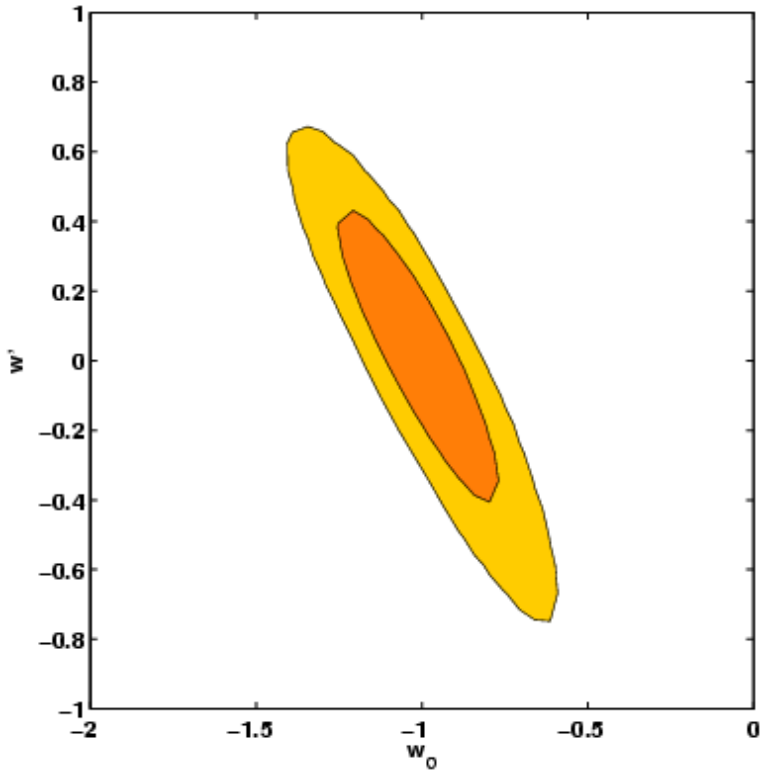
Constraints from Con-X fgas data alone with 5% measurement errors, 4% systematic scatter in b, 2% priors on $\Omega_b h^2$, h and b.

Evolution model: $w(a)=w_0+w_a(1-a)=w_0+2w'(1-a)$. Comparable accuracy and beautifully complementary to LSST, SNAP, Planck (and cluster growth).

The improvement: Con-X vs current data



Con-X fgas + CMB data (non-flat: no `hidden' priors!)



Evolving DE model:

$$w = w_0 + w_a(1-a)$$

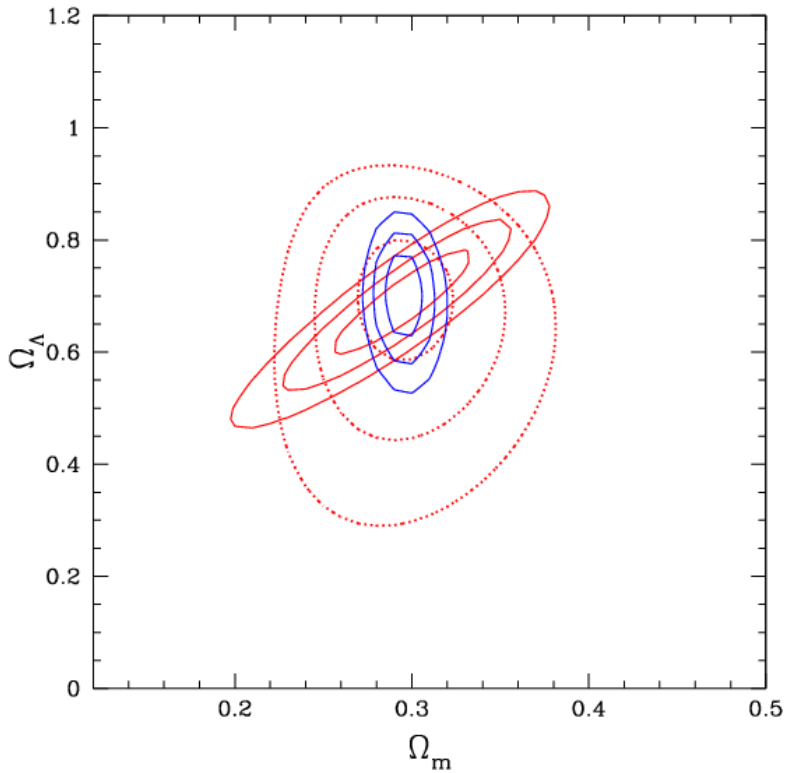
$$w = w_0 + 2w'(1-a)$$

$$w' = dw/d\ln a$$

$$a = 1/(1+z)$$

Above constraints are for Con-X + WMAP 8 year data (TT only). This is a conservative estimate of what will be possible. The constraints from Con-X will be of comparable accuracy and beautifully complementary to the best other constraints from LSST, SNAP, Planck and galaxy cluster growth studies.

Expected Con-X X-ray+SZ studies



Blue curve: fgas results

Red solid: X-ray+SZ with `perfect' flux calibration.

Red dotted: X-ray+SZ with 2% flux calibration.

Though not as precise as fgas, the X-ray+SZ experiment provides additional, complementary constraining power on dark energy based on an a very different set of assumptions. e.g.X-ray+SZ results are independent of b(z).